Long-term AeroCube Solar

JH Lee, D Walker, JC Nocerino, BS Hardy, DA Hinkley, SH Liu, CJ Mann, YY Lao, DL Turner, JB Blake, WR Crain
Physical Sciences Laboratories

24 April 2018

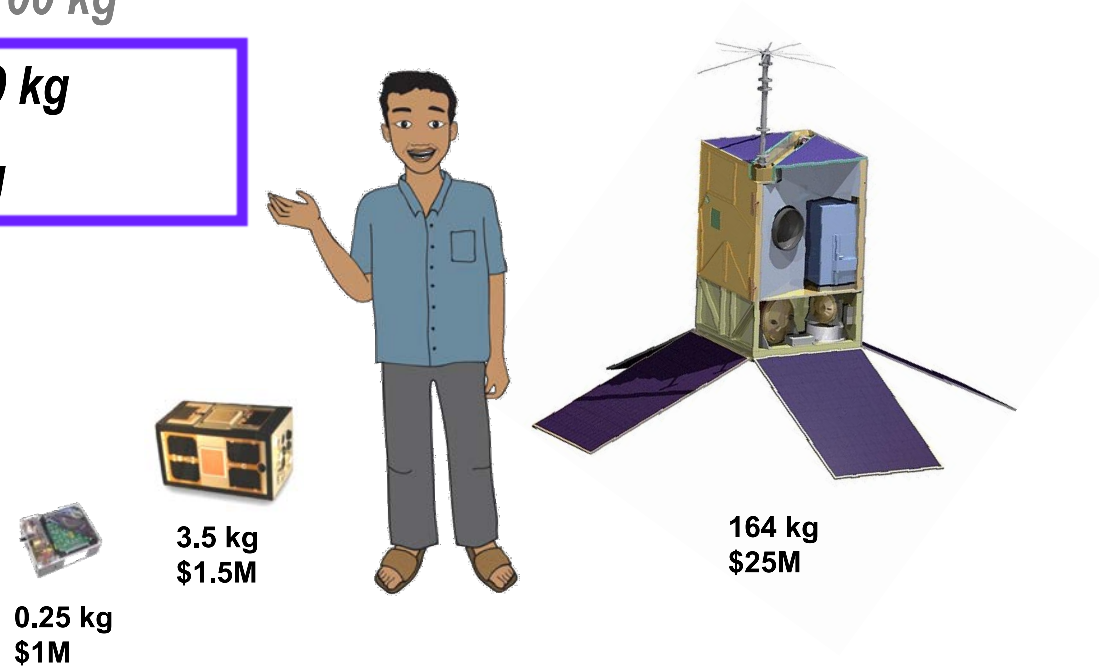
We gratefully acknowledge the Customer and Aerospace's Sustained Experimentation and Research for Program Applications (SERPA) Program. We also acknowledge the Multi-Program Acquisition and Capability Enhancement (MPACE) Program with support from the US Air Force Space and Missile Systems Center Advanced Systems and Development Directorate (SMC/AD).

Outline

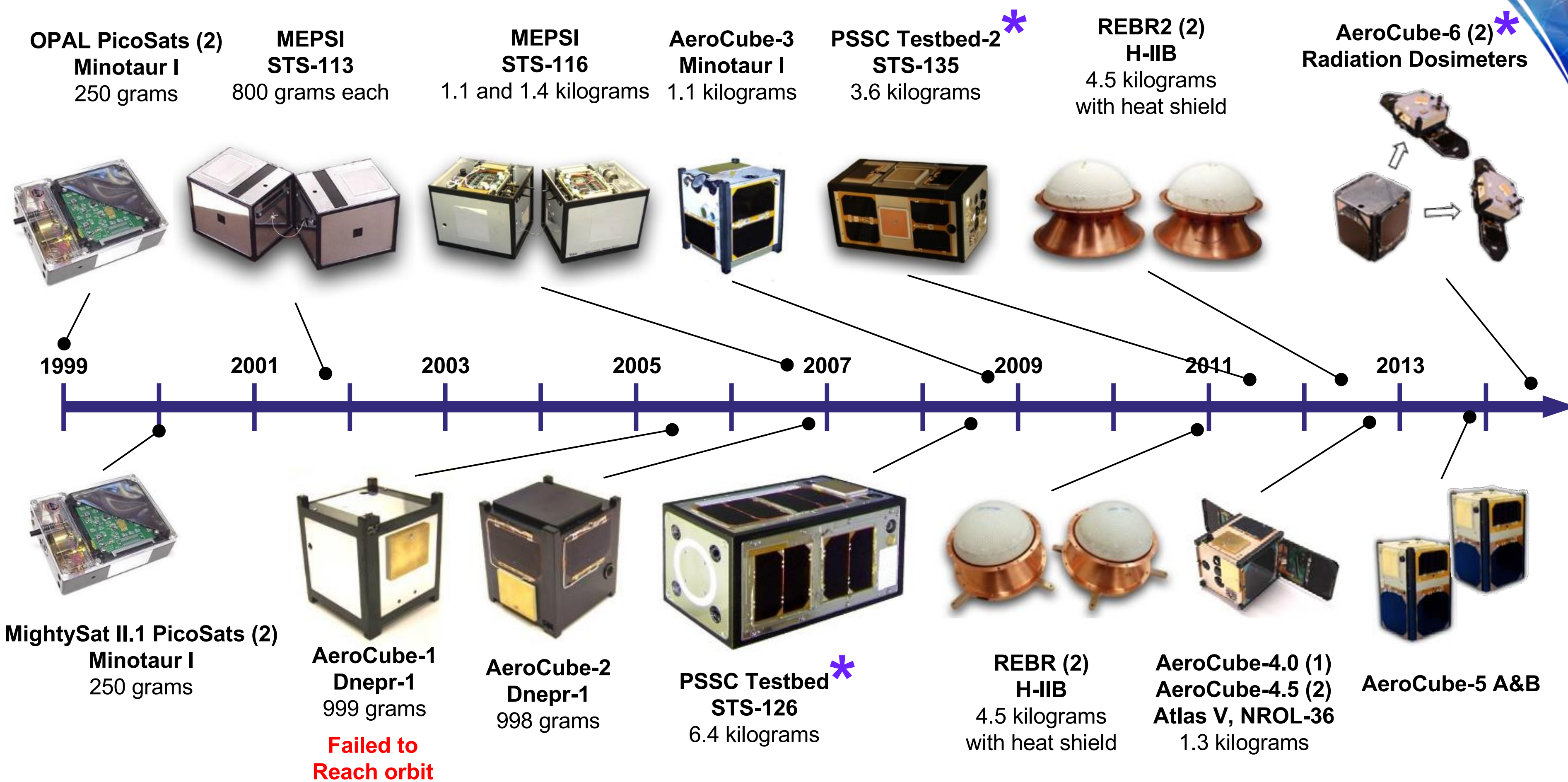
- *Overview of PICOSAT/AeroCube Program Outlook and Activities*
- *Concepts & Development*
  - *Test and evaluation of space solar cells*
- *On-orbit measurements*
  - *Telemetry*
  - *Characterization for comparison to ground testing*
- *Lessons learned and knowledge transfer to future missions*

Satellite Sizing Guidelines

Standard satellite	*> 1000 kg*
Minisatellite	*= 100-500 kg*
Microsatellite	*= 10-100 kg*
Nanosatellite	***= 1-10 kg***
Picosatellite	***< 1 kg***

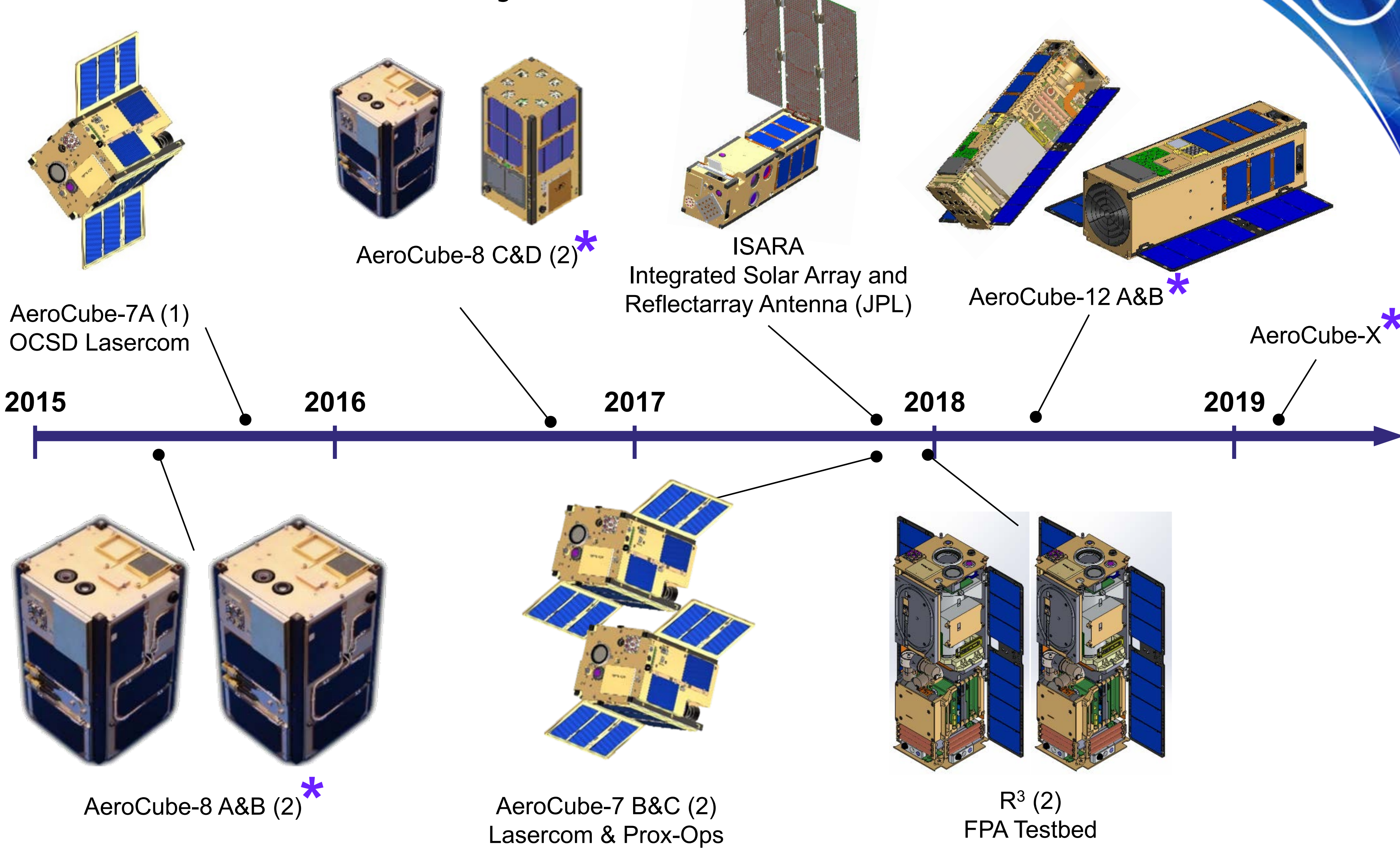


Aerospace Nano/PicoSatellite History (1999-2015)



- *Missions typically employ high-capacity LCO 18650 COTS cells for operations*
- *Multijunction space solar cells providing energy generation needed to support bus, charge Li-ion cells, and power payloads*
- * *Space solar cell experiment payload*

Timeline of Active Projects

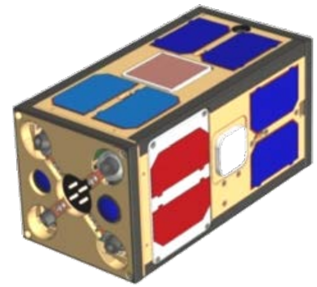


- ***More recent missions employ high-capacity LCO 18650 COTS cells for operations and high-rate spinel 18650 COTS cells to support beaconing or laser comm***
- ****Space solar cell experiment payload***

Evolving Technologies

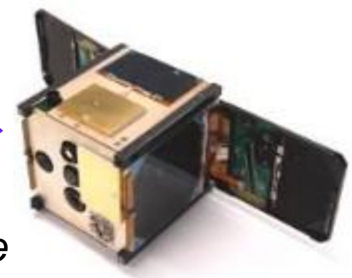
1. TRL-raising missions

- *Fly new space solar cell type in space for first time while also testing bus and attitude control*

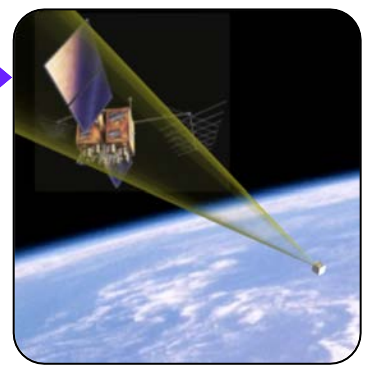


2. Test objects for others

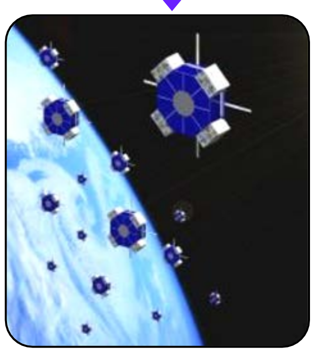
- *Characterize performance of contractor's new technology in space*
- *Compare high precision space data to high precision lab data*



3. New kinds of missions



Mother/daughterships
Satellite augmentation



Distributed assets

Progression of mission difficulty

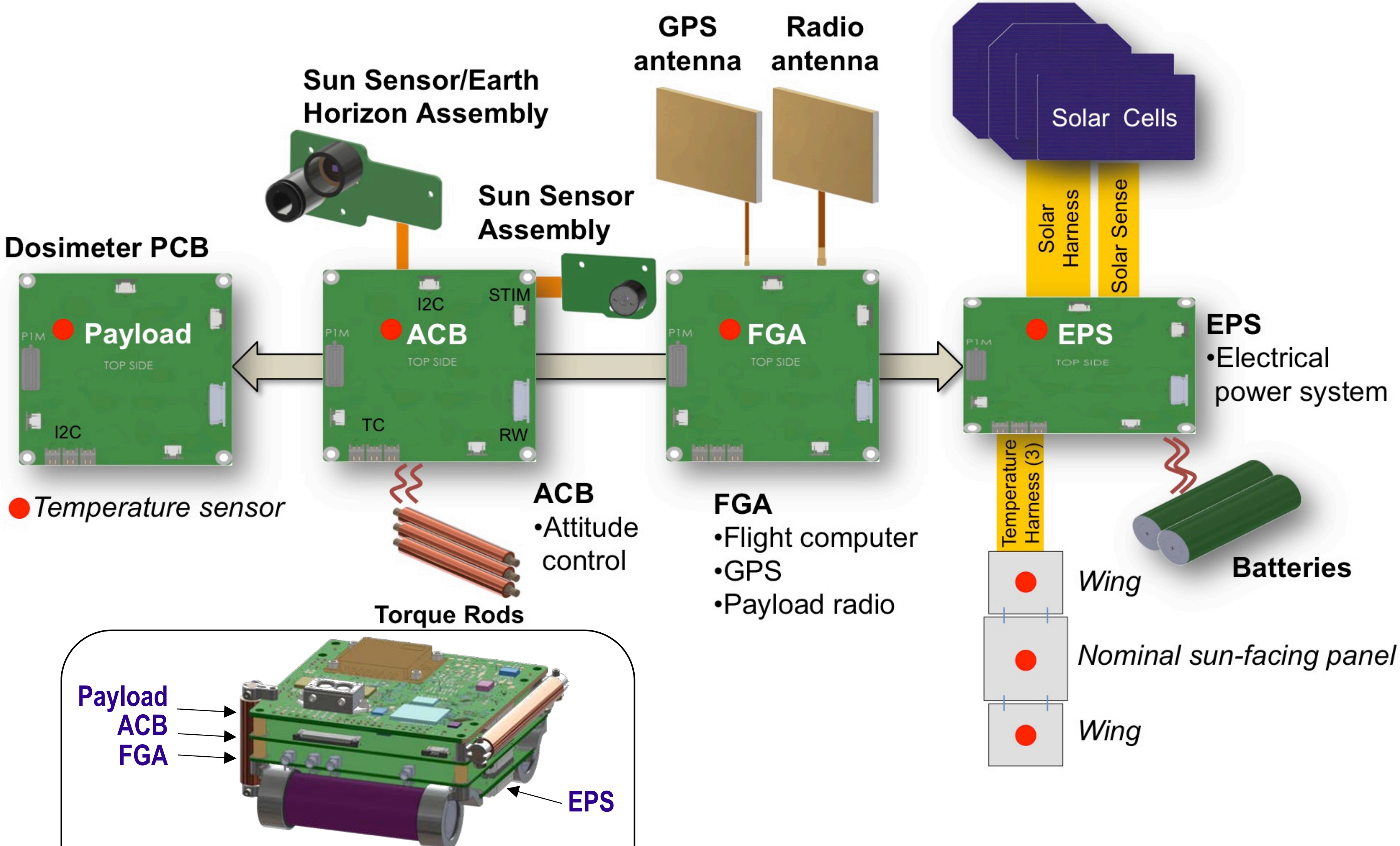
Capability Progression

2005 – Present

- Radio (low data rates)
- Rechargeable power system
- Flight computer (robust)
- Camera (low resolution)
- Magnetic sensors
- Rotation rate sensor (low stability)
- Reaction wheels
- Torque coils
- Tethers
- Sun and Earth sensors
- Cold gas propulsion
- Solid rocket motor
- On-orbit reprogrammability
- Encrypted communication
- Camera (med resolution)
- Rotation rate sensor (inertial grade)
- Deployable solar panels
- Attitude control algorithms
- Launch environment logger
- Autonomous ground operations
- Optical beacon
- Autonomous satellite operation
- Radio (high data rates)
- Proximity radar
- Laser communication (10MB/s)
- Continuous Command & Control
- Electric propulsion
- Camera (high resolution)
- Local Area Networks (LAN)

Key:
Multiple Flights
Single Flight
Under Development

Mature AeroCube Bus



Modular bus architecture supports add-on of payloads

AeroCube Concepts and Development

The Energy Technology Point of View

Identify available battery and space solar cell technologies

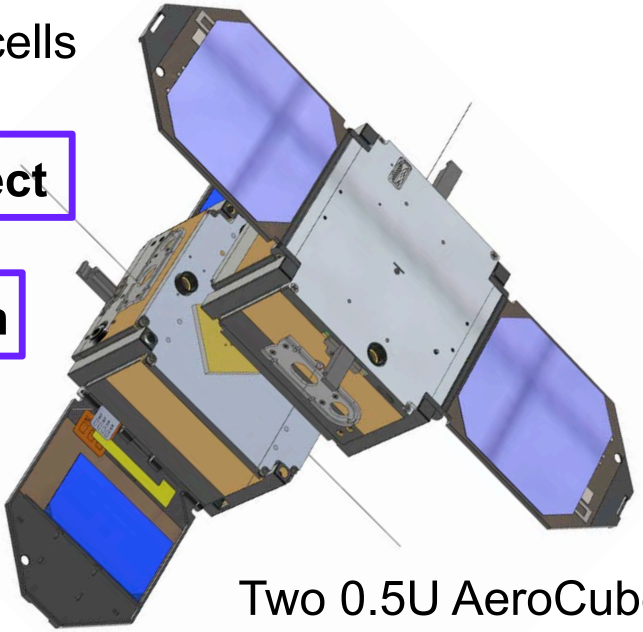
Power requirements and actual power capabilities

Size, mass and volume requirements

- Generally limits selection to Li-ion 18650s or pouch cells and multijunction space solar cells

Test, evaluate, and select

Deliver for integration



Two 0.5U AeroCubes

Identify and test new technologies to meet all SWAP requirements

Some high energy density materials currently not scalable but perfect for CubeSat

Space Solar Cell Technology Test and Evaluation

Seven step procedure

Step 1. Physical characteristics
a) Visual inspection for any damage upon shipping receipt
b) Electroluminescence (EL) inspection to probe cell uniformity and identify possible defects

Step 2. Baseline electrical characteristics
a) Cell light I-V
b) Cell temperature coefficients

Step 2a. Baseline spectral response, quantum efficiency, dark I-V
a) Additional cell evaluation methods for detailed investigation of cell characteristics
b) Option for AeroCube flights

Establish Baseline →

Step 3. Cell mounting
a) Mount cells onto AeroCube

Step 4. Vibration
a) Vibration of fully integrated system
b) Visual inspection for any changes following vibration

Step 5. Vacuum Bakeout
a) Vacuum bakeout of fully integrated system
b) Visual inspection for any changes following bakeout

Environmental Test (For AeroCube Flight) →

Step 6. Post-environmental test characteristics
a) Cell light I-V for comparison to Step 2 baseline data
b) EL inspection to further investigate if changes in cell performance observed

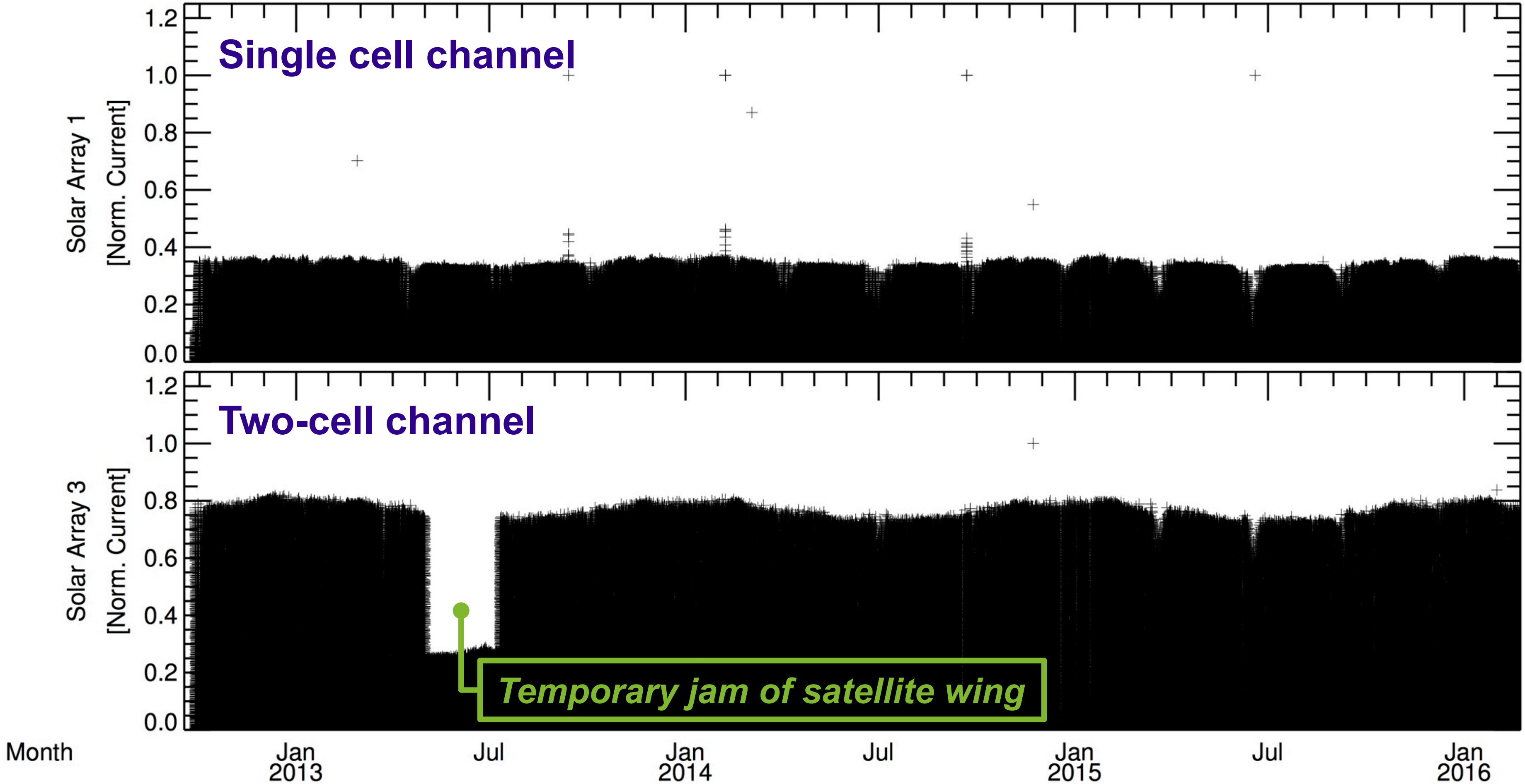
Step 7. Final flight acceptance
a) Cell light I-V for comparison to Steps 2 and 6
b) Accept or reject cells for flight
c) Archive final flight acceptance data for later comparison to on-orbit data

Evaluate and Select (For AeroCube Flight)

Performance test procedures have been used successfully on space solar cells supporting several operational missions

AeroCube-4 Solar Array Telemetry

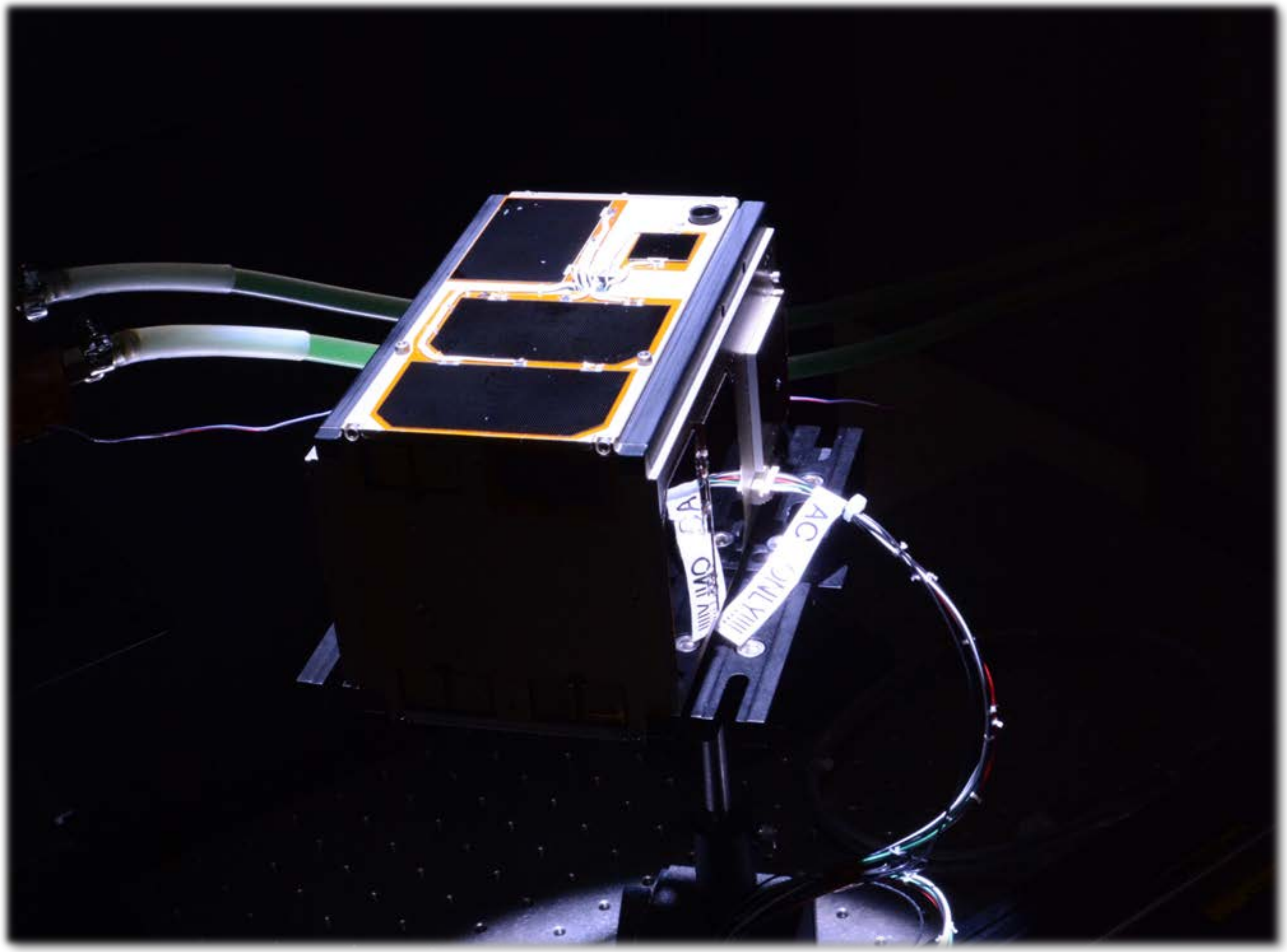
Solar array channel normalized short circuit current telemetry suggests no significant degradation has occurred after 3+ years on orbit



Multijunction space CICs supporting AC4 3+ years

Space Solar Cell Research on AeroCubes

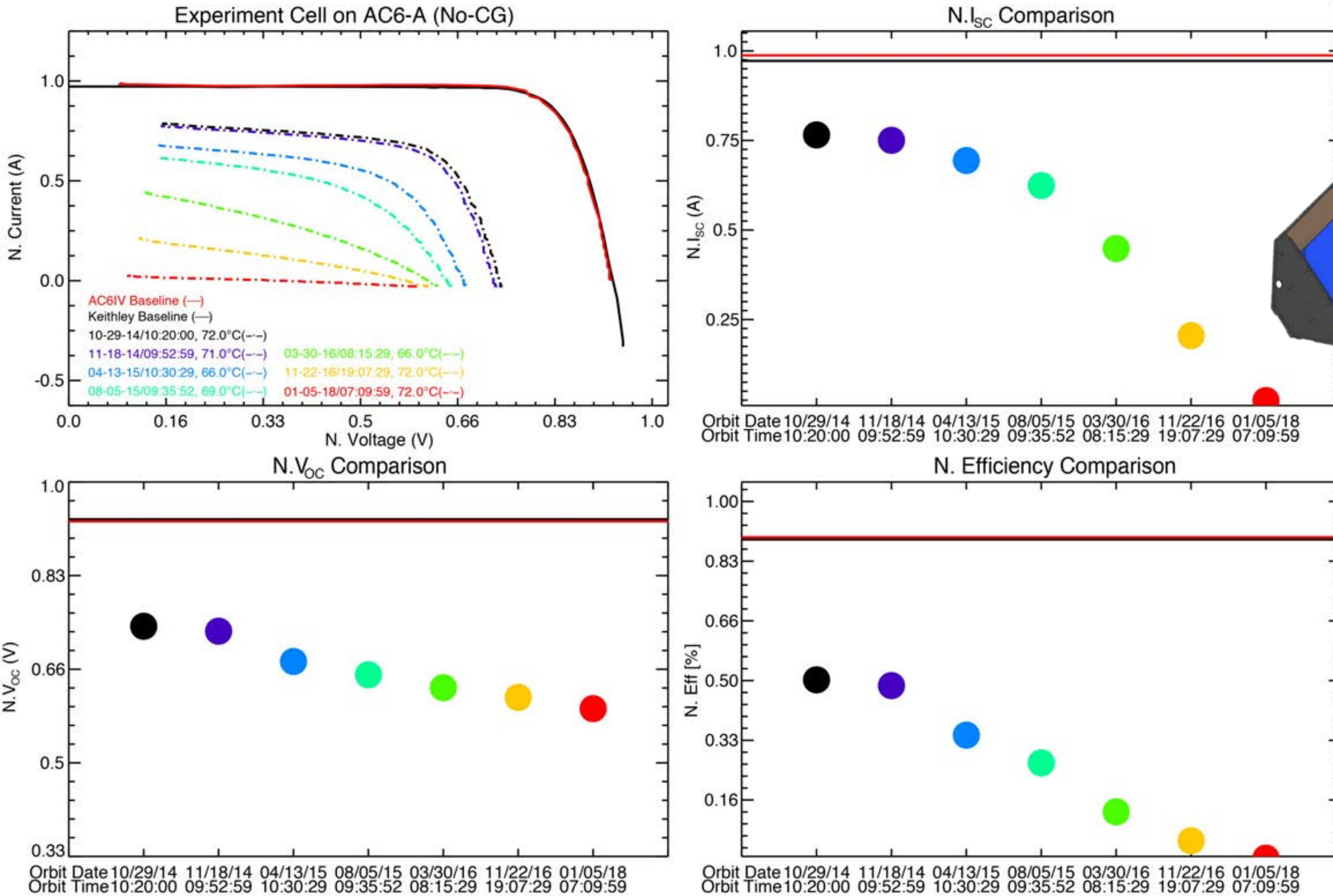
A Decade of Experience

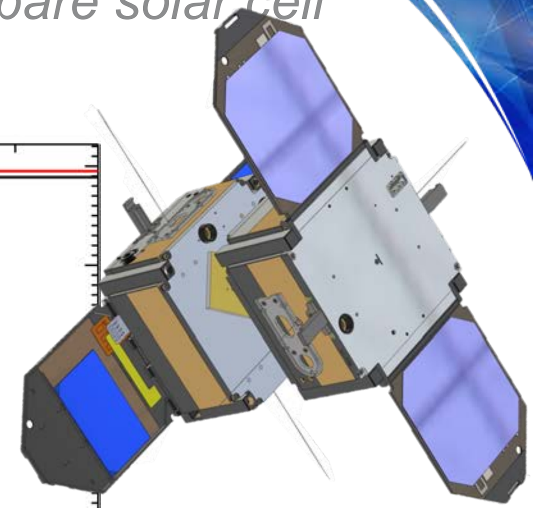


Calibrated AM0 (air mass zero) light source illuminates solar cells for final measurements before flight hardware delivery in 2015

AeroCube-6 Solar Cell without Cover Glass

AC6 observations of space environment exposure on a bare solar cell from Oct 2014 to Jan 2018

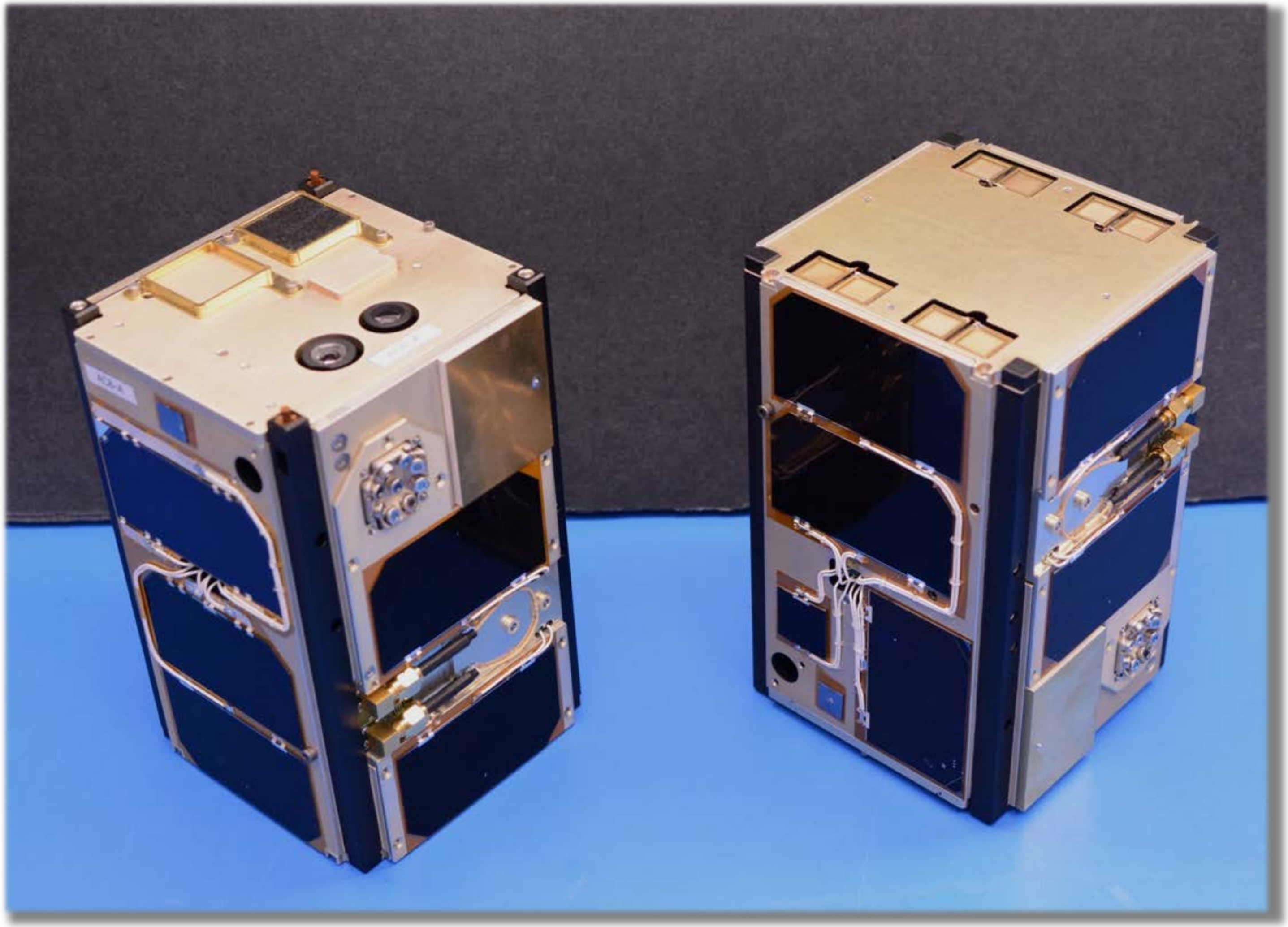




AeroCube-6 consisted of two 0.5U CubeSats with similar instrumentation and orbit

AeroCube-8 Mission

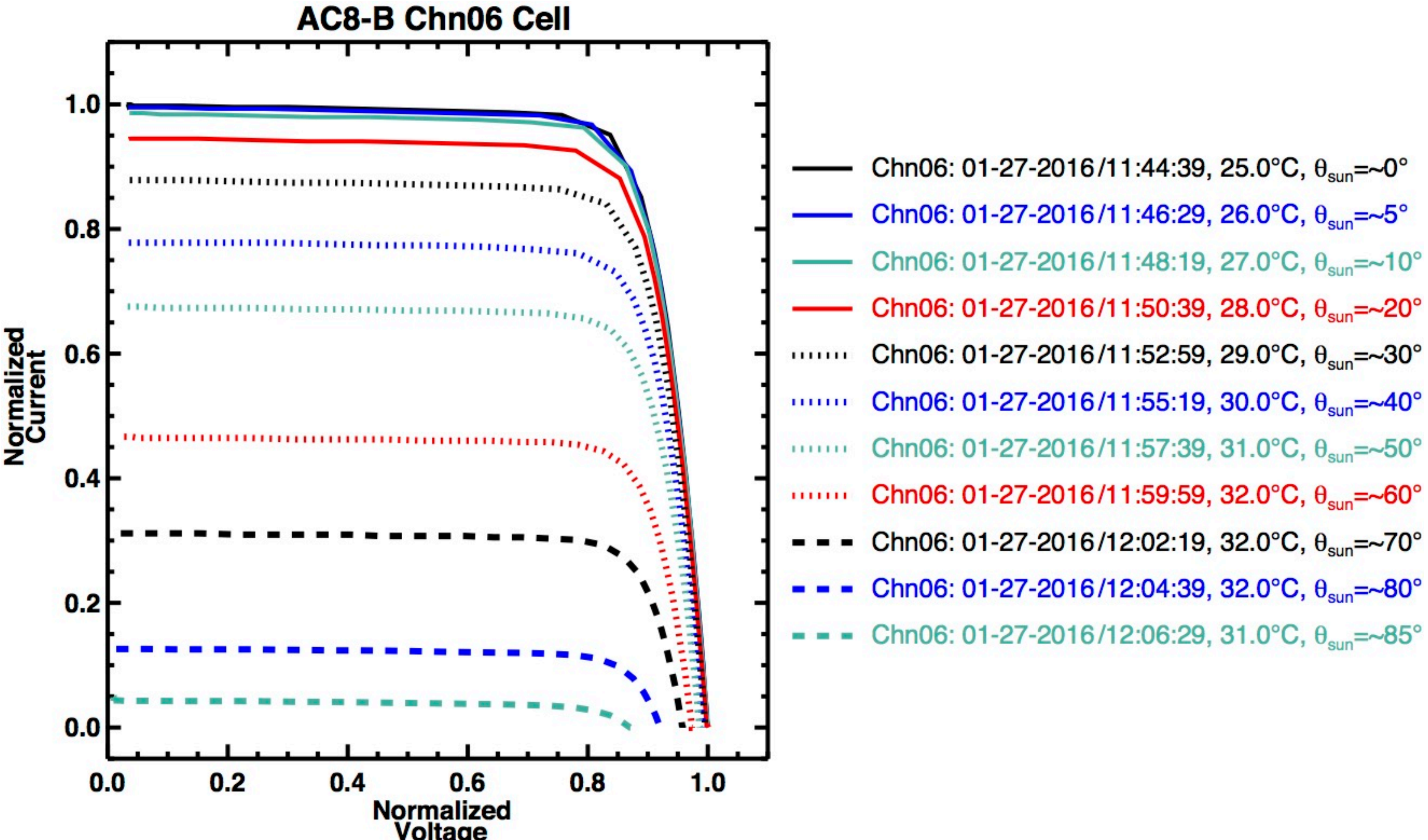
AeroCube program's most recent space solar cell experiment



Demonstration of several payloads, including on-orbit characterization of 5 unique multijunction space solar cell technologies

AeroCube-8 Space Vary Angle of Incidence (1/2)

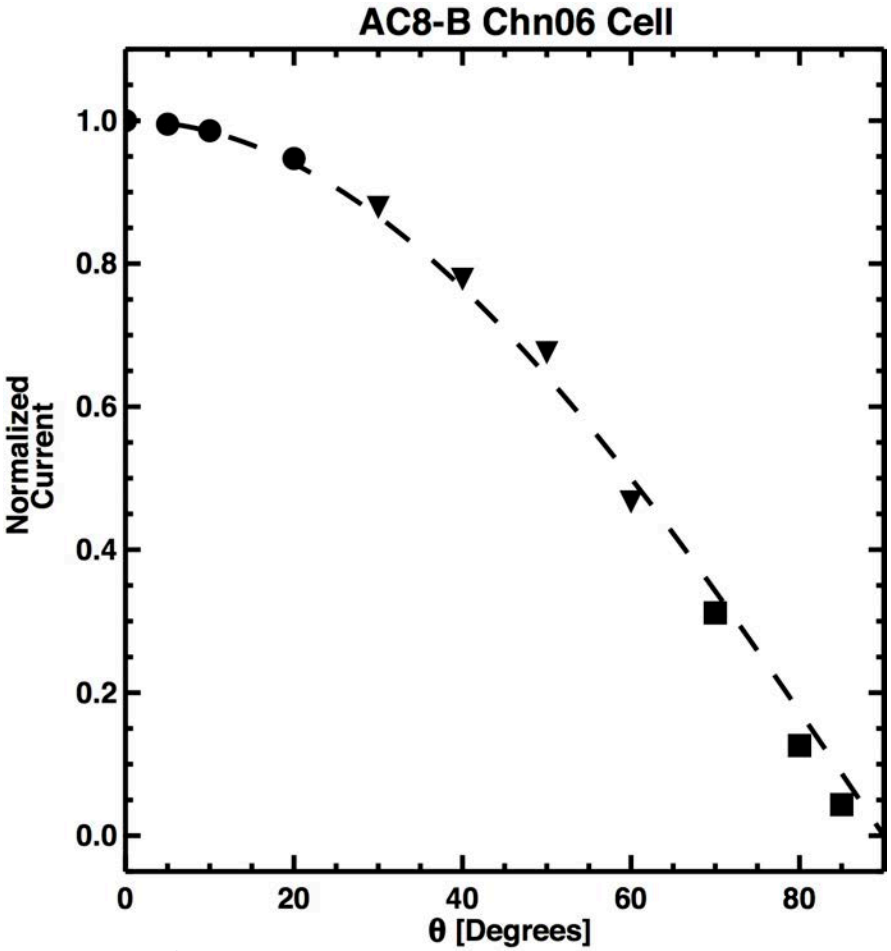
First on-orbit AIAA S-112 test over full range of solar incidence angles



- ***Developed, scheduled, and executed on-orbit S-112 "Vary angle of incidence" measurement sequence during low beta angle interval***
- ***Collected measurements for all cell technologies that were instrumented***

AeroCube-8 Space Vary Angle of Incidence (2/2)

First on-orbit AIAA S-112 test over full range of incidence angles



- ***Dashed curve is the cosine function***
- ***Symbols are normalized I_{SC} over-plotted as a function of solar incidence angle***
- ***Close match to cosine curve demonstrates success of measurement sequence***

Comparison of on-orbit and lab radiometric calibration measurements

- Latest space cell technologies lack primary high altitude-flown standards
- Spectral response measurements can be used to inform on-orbit performance
  - *Spectral response of each sub-junction convolved with known solar spectrum (ASTM E490) to yield expected sub-junction currents ($J_{e,S}$)*
  - *Sub-junction spectral response also convolved with solar simulator (Spectrolab X-25) spectrum to yield instantaneous sub-junction currents ($J_{i,S}$)*
  - *Tune simulator spectrum until $|J_{i,S} - J_{e,S}|/J_{e,S} \leq 1\%$ for $_{S\ =\ \text{Sub-junction 1, Sub-junction 2, etc.}}$*
  - *Acquire light I-V measurements*

Comparison between laboratory and on-orbit data (11-15-2016/20:33:41)

****On-orbit I_{SC} and Efficiency both corrected for Sun-Earth distance***

Comparison represented using percentages to protect vendor-proprietary data

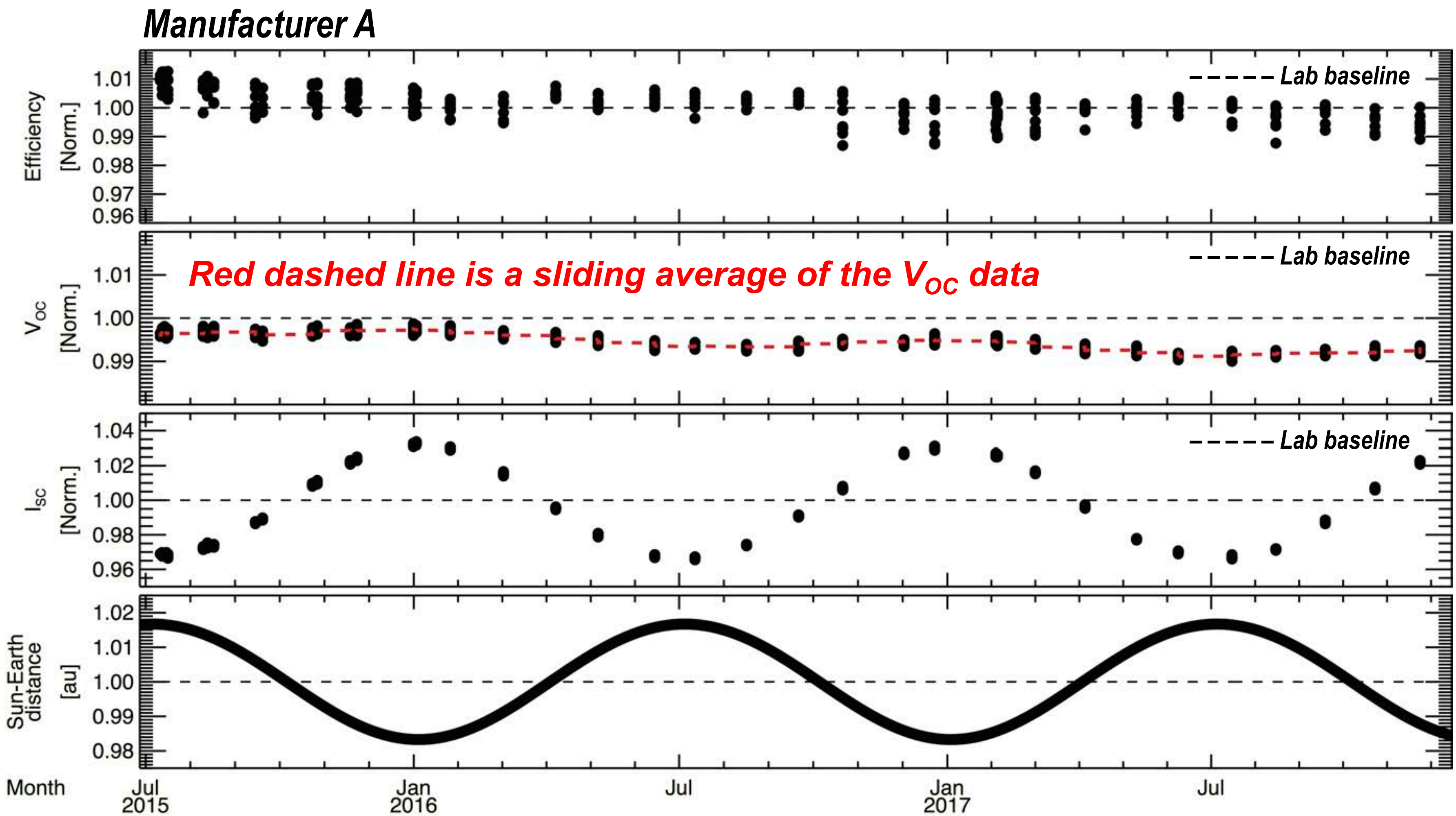
NOTE: n < 0 indicates the on-orbit value was higher

Measured Date & Time	Cell Description	V_{OC} (V)	I_{SC}* (A)	FF	Efficiency* (%)
06-09-2016/13:53:02	Cube_Cell_iso	1.00%	0.78%	0.00%	0.52
06-09-2016/17:30:43	Cube_Cell_radio	0.62%	1.32%	-0.24%	0.51

Cell performance measured after laboratory radiometric calibration is comparable to BOL on-orbit measurement.

Long-term AeroCube-8 on-orbit data

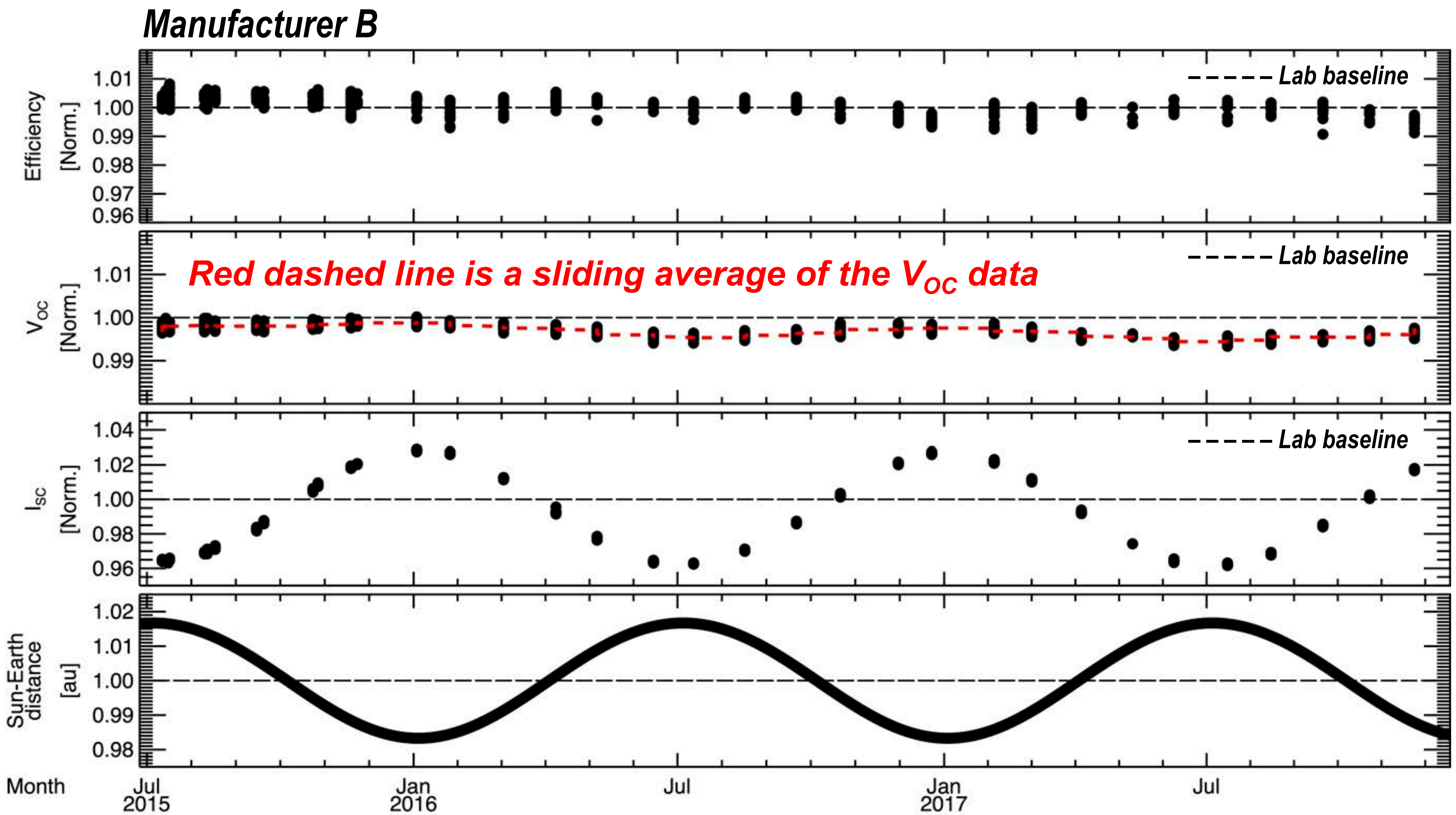
Data from July 2015 – December 2017



>2.5 years of I-V data enables studies of degradation trending for comparisons to ground irradiation testing and degradation modeling

Long-term AeroCube-8 on-orbit data

Data from July 2015 – December 2017



>2.5 years of I-V data enables studies of degradation trending for comparisons to ground irradiation testing and degradation modeling

Gaps in understanding on-orbit solar cell degradation

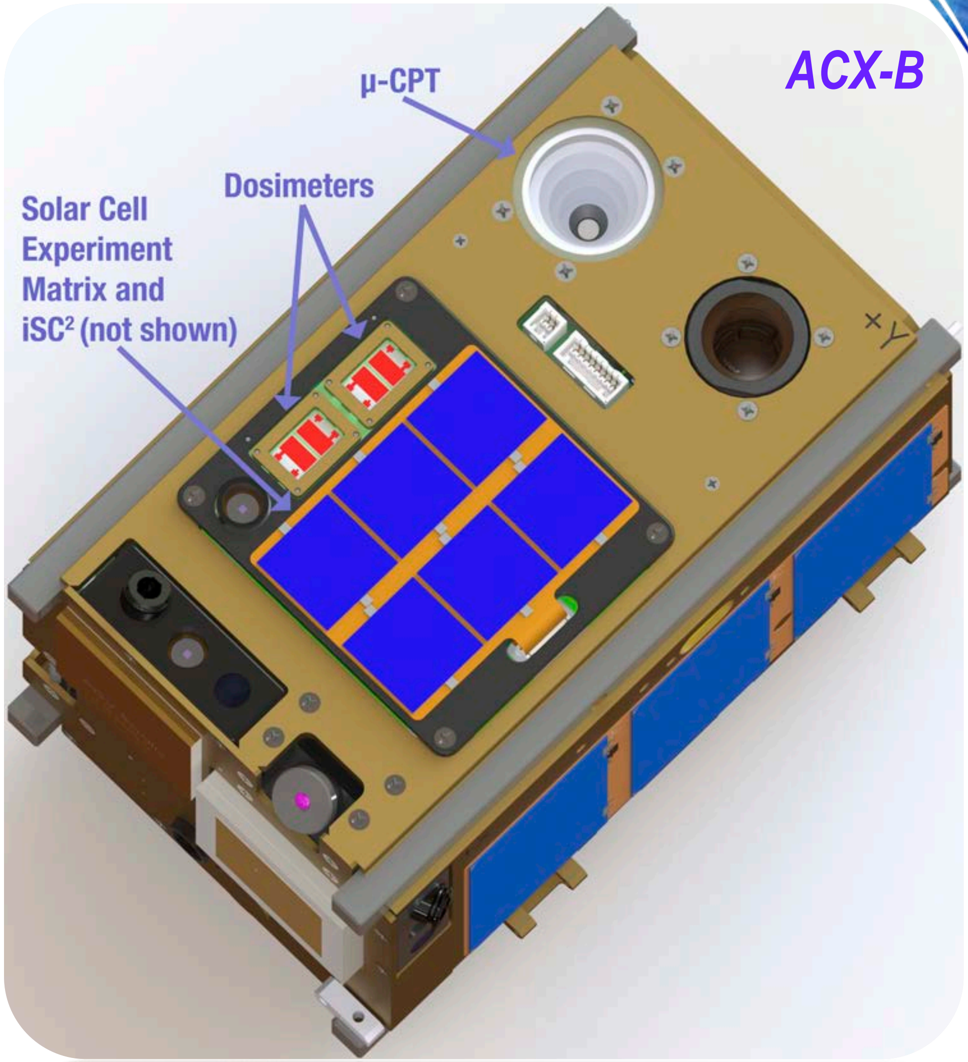
- Two known solar cell degradation models with unknown accuracy: JPL EQFLUX and NRL SCREAM (solar cell radiation environment analysis model)
  - *Questionable which degradation predictions from the models are more representative of actual on-orbit degradation*
- Radiation environment models (AX8 & AX9) based on different datasets from different satellites add additional uncertainty to cell degradation predictions
  - *Applications of AX8 & AX9 model outputs (integral fluences) to solar cell degradation model comparison efforts do not constrain degradation model uncertainties*
- Objective method to observe on-orbit solar cell performance and degradation is needed
  1. *On-orbit instrumentation shall measure solar cell performance as well as the charged particle radiation thought to be most relevant to solar cell degradation*
  2. *On-orbit solar cell measurements shall be compared to results generated by typical irradiation testing and degradation modeling methods*
  3. *On-orbit charged particle measurements shall be applied to irradiation testing and degradation modeling for comparison to #2*

An on-orbit experiment will help improve our understanding of solar cell degradation and motivate development of more accurate lab tests and models.

AeroCube-X solar cell radiation experiment

Current-voltage, space weather and environment effects payload (IV SWEEP)

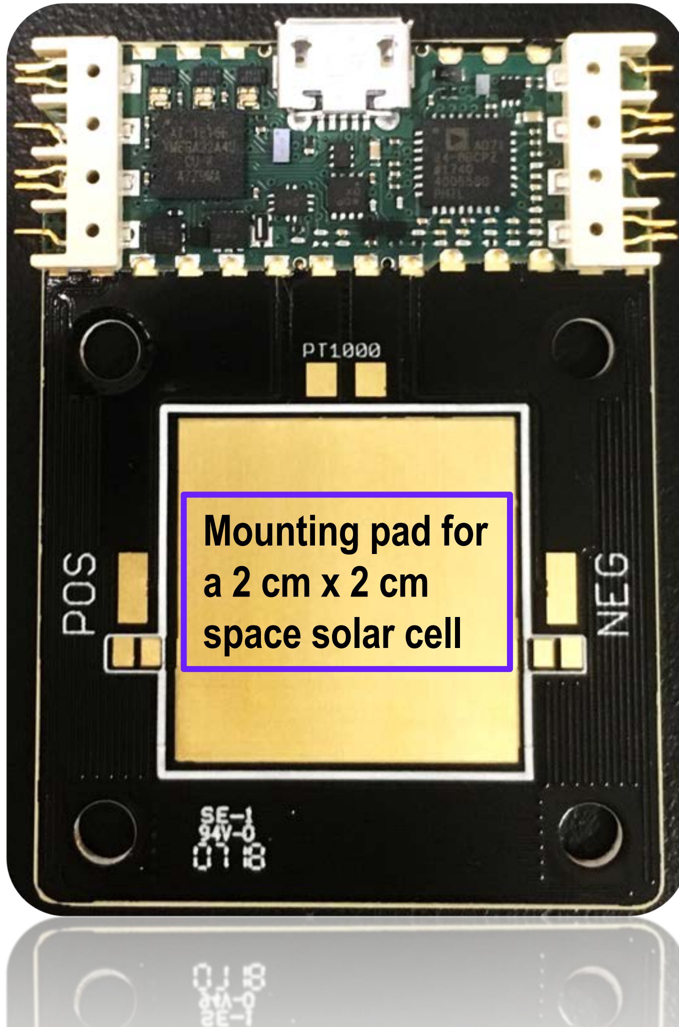
- **Objective:** Observe in situ performance and degradation of solar cells with knowledge of the charged particles causing the degradation
- ***iSC²*** (intelligent solar cell carrier; patent pending) integrated to ***solar cell experiment matrix*** measures high precision I-V and temperature characteristics of solar cells with and without cover glass; goal to fly a balloon-flown reference cell as part of matrix
- ***Dosimeters*** measure total radiation dose
- ***µ-CPT*** (micro-charged particle telescope; ACX-B only) measures proton and electron differential energy fluxes needed to calculate integral fluences
  - *High resolution measurements of radiation belt particles that can cause SEEs and degrade technology and materials*
  - *Data applicable to improving lab space environment effects testing and modeling*



Collaboration among labs and AeroCube Program to develop a payload and radiation flight experiment for characterizing performance and degradation of space cells

IV SWEEP instrumentation: iSC^2 source measurement unit

Patent-pending technology acquires accurate IV and temperature characteristics of space solar cells



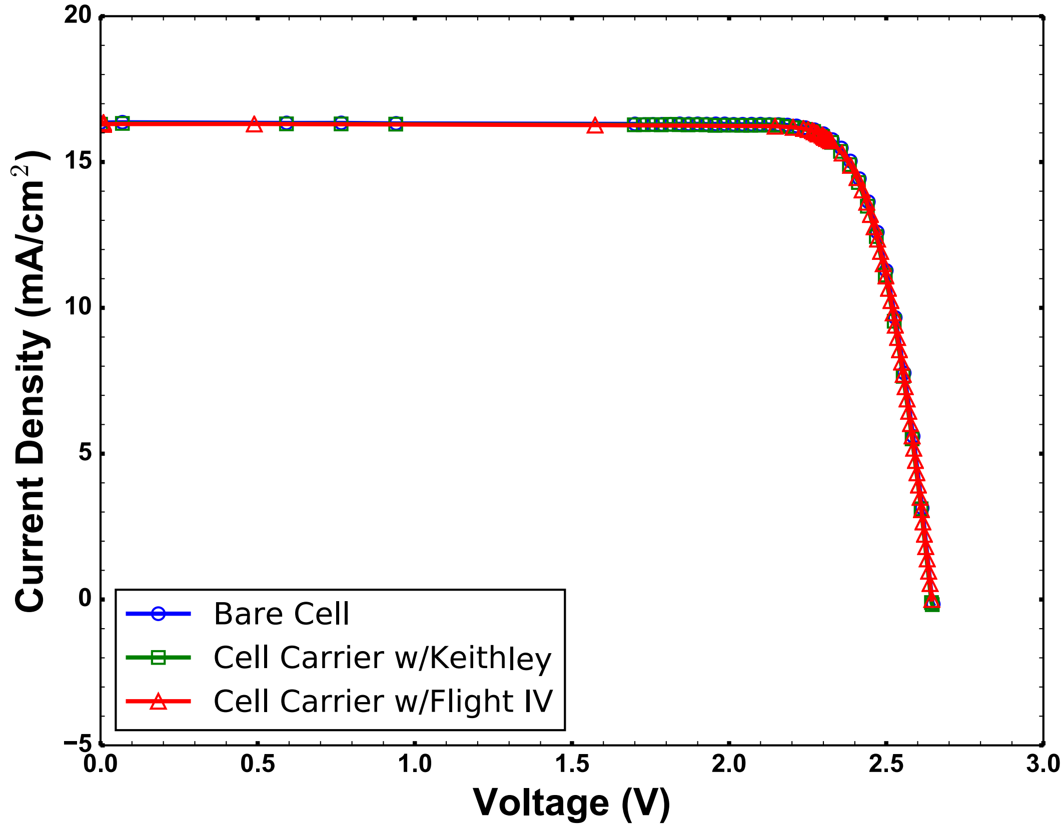
iSC^2 solar cell characterization electronics

Cell carrier for balloon or high altitude aircraft flights

Version of iSC^2 already fabricated and delivered due to parallel effort to conduct high altitude balloon flights for space solar cell calibration.

IV SWEEP instrumentation: iSC² source measurement unit

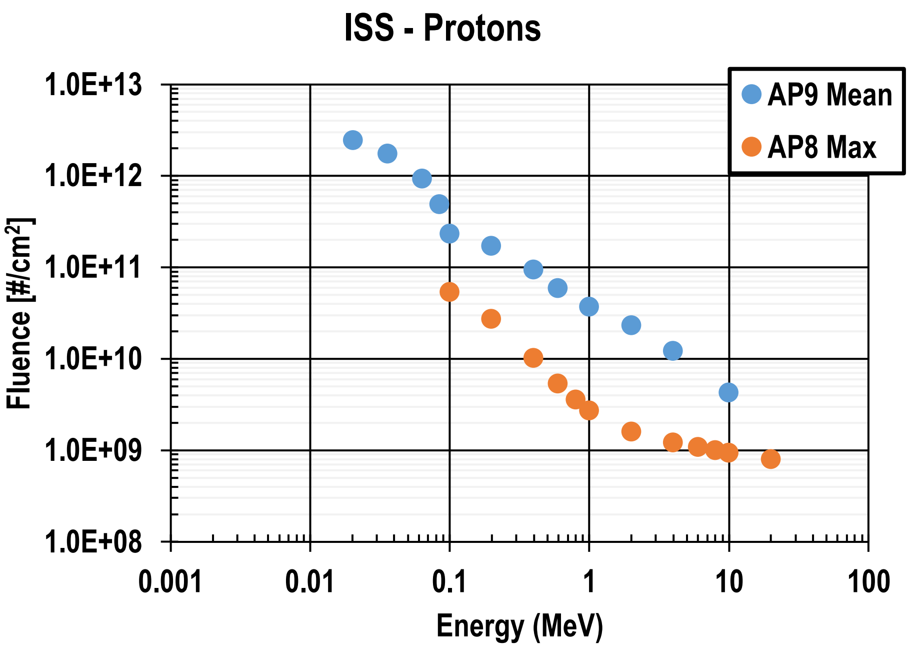
iSC² enables zero-error solar cell IV measurements



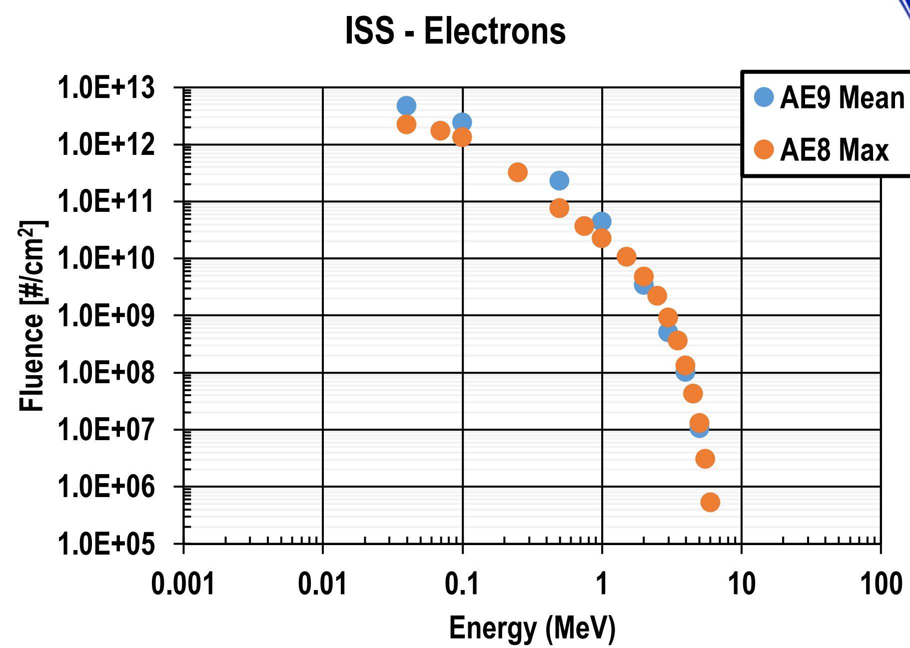
Comparison of measurements taken with a Keithley source meter and the iSC² source measurement unit show near-identical data

AeroCube-X instrumentation and payload design

Space environment model runs to inform payload design



- Low-energy (0.05-0.2 MeV) protons can quickly degrade bare solar cells
- Determine effect of predicted proton fluences on test solar cells of same type to be flown
- Use initial test outcomes to define low-energy threshold of μ-CPT (~0.08 MeV)



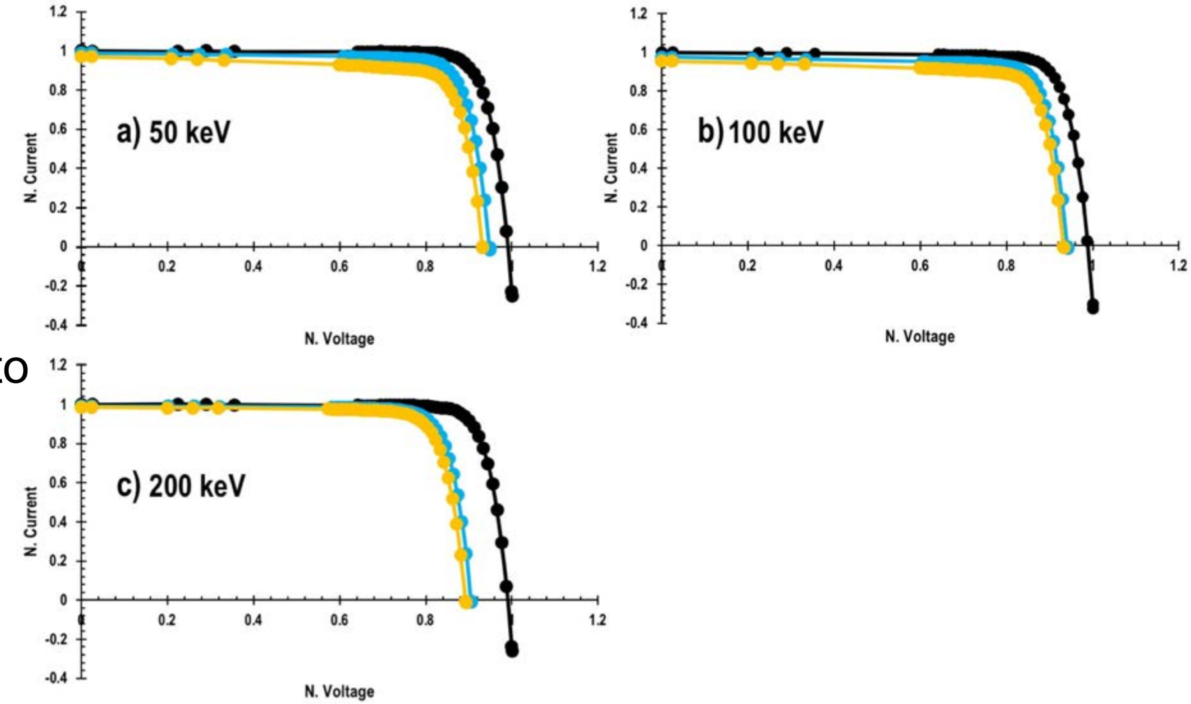
- Lab solar cell electron irradiation tests typically begin near ~0.3 MeV energies
- Ensure combined dosimeter and μ-CPT instruments can measure these electrons in space
- Future electron irradiation tests planned

Used AX8 and AX9 (v1.30.001) radiation environment models to get predicted particle fluences in ISS orbit.

AeroCube-X instrumentation and payload design

Ground tests for instrument requirements and future comparisons to space data

- AP9 mean ISS proton fluences to test solar cells of same type to be flown
  - *Well-known that protons can quickly degrade cells without cover glass*
- Determine sensitivity of cell to proton energies
- Ensure μ-CPT can measure these protons
- Data for comparison to eventual on-orbit data



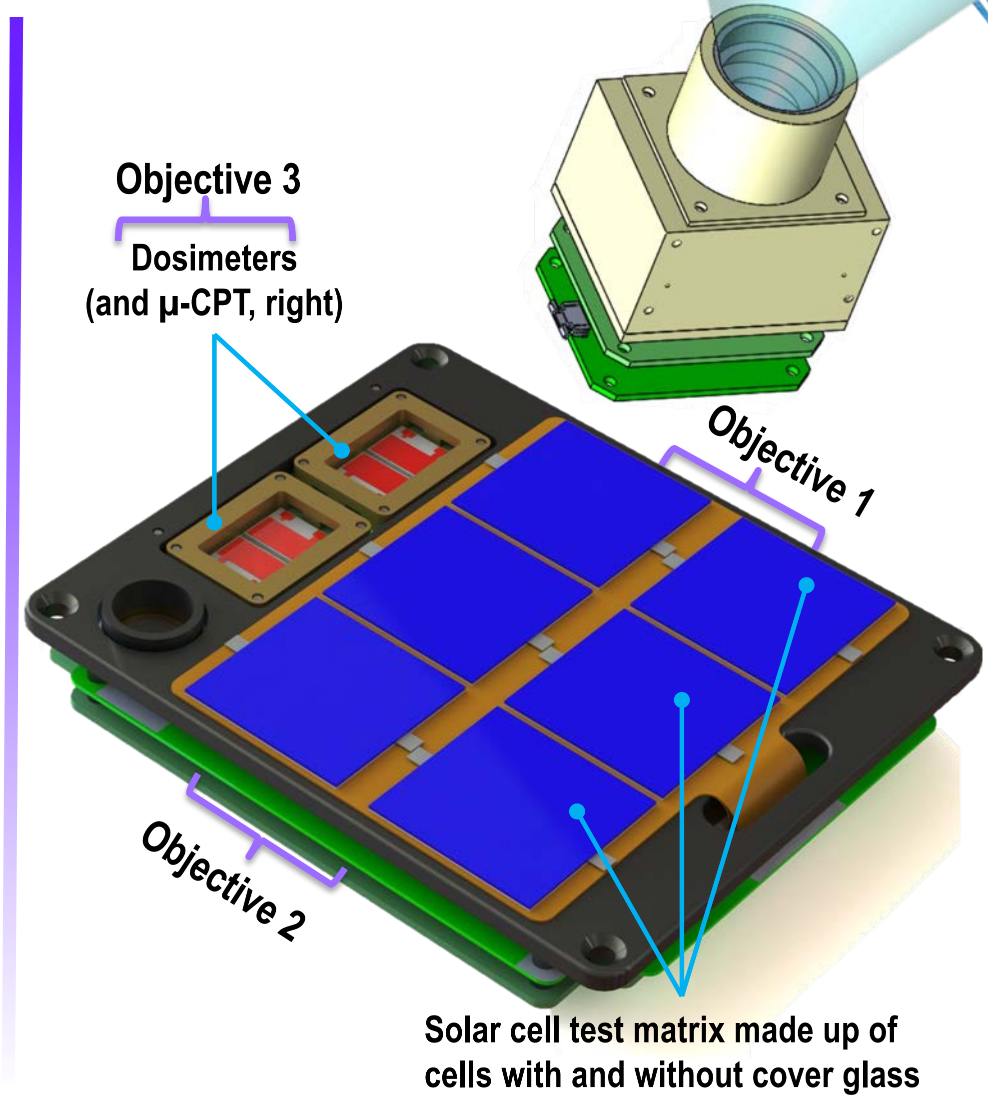
Energy (keV)	Step 1 Fluence	Step 2 Fluence	Step 3 Fluence	Target Total Fluence
50	1E+10	2E+10	7.32E+10	1.032E+11
100	1E+10	1E+10	8.75E+9	2.875E+10
200	1E+10	1E+10	1.68E+9	2.168E+10

AeroCube-X instrumentation and payload design

IV SWEEP fits within a 1.5U CubeSat alongside other payloads

Achieving experiment objectives:

1. Measure space performance of well-characterized solar cells with standard (150µm/6mil) cover glass as experiment control (2 cells)
2. Observe degradation of solar cells with thinned cover glass and without cover glass as a function of mission lifetime (2 cells with 1-2 mil covers, 2 cells without covers)
3. Measure the actual environment causing degradation for comparison to ground tests conducted using observed and modeled (AX8/9) particle fluences
   - *µ-CPT Electrons: ~0.05 MeV to 5 MeV*
   - *µ-CPT Protons: ~0.08 MeV to 3.3 MeV*
   - *Dosimeters: configurable energy ranges*
   - *µ-CPT on ACX-B only; Dosimeters on both ACX-A and ACX-B*



IV SWEEP instrumentation may be applicable to monitoring solar array performance on larger platforms.

Lessons Learned and Knowledge Transfer to Future Missions

- ***Multijunction space solar cells have provided power to AeroCube bus and payloads required to achieve mission goals***
- ***Recent results show AeroCube platform as high precision space solar cell characterization capability***
  - ***Viable method to obtain BOL on-orbit data within a technology's development cycle***
  - ***Stable platform enables studies of long-term trends using the accurate on-orbit measurements***
    - ***EOL studies: comparisons to ground testing and cell degradation modeling***
  - ***Future flights to investigate end-to-end performance and degradation of space solar cells***

Questions?

Thank you!

Long-term AeroCube Solar

JH Lee, D Walker, JC Nocerino, BS Hardy, DA Hinkley,
SH Liu, CJ Mann, YY Lao, DL Turner, JB Blake, WR Crain

Physical Sciences Laboratories

We gratefully acknowledge the Customer and Aerospace's Sustained Experimentation and Research for Program Applications (SERPA) Program. We also acknowledge the Multi-Program Acquisition and Capability Enhancement (MPACE) Program with support from the US Air Force Space and Missile Systems Center Advanced Systems and Development Directorate (SMC/AD).